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13. ABSTRACT (Maximum 200 Words)

Conventional mammography only evaluates the spatial arrangement of tissue in the breast, as it depends upon the fact that some materials absorb x-rays more than other materials (the x-ray energy must be deposited in the body to produce an image). We propose to investigate the potential of x-ray polarization imaging, by building an x-ray polarimeter (a device designed to measure polarization) and determine the factors that affect polarimeter design. Polarization radiography has the potential to supplement mammographic images with information about the function, composition, and metabolism of the breast. We plan to perform fundamental experiments regarding x-ray polarization to determine whether the effect is sufficiently large to allow it to be used to produce images. We also wish to measure the ability of key biological materials, including breast tissue, to alter the polarization of x-rays, and determine the accuracy with which we can measure this effect. This research is quite clearly, speculative, but the program described in the grant would give the experimental data necessary to clearly understand the benefits and limitations of attempting to image tissue using polarized x-rays. This annual report presents our research to date.

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1. Introduction

X-rays are transverse waves; thus, one can preferentially produce x-rays in one polarization state. Passing through biological tissue, this state of polarization may be changed. Since x-rays are capable of passing through many inches of tissue, changes in the polarization state can reflect information about the tissue deep inside the body.

Conventional mammography only evaluates the spatial arrangement of tissue in the breast, as it depends upon the fact that some materials absorb x-rays more than other materials (the x-ray energy must be deposited in the body to produce an image). This new approach has the potential to supplement mammographic images with information about the function, composition, and metabolism of the breast. The ability to rotate the polarization of x-rays is conferred by the passage of the x-rays through the body, not the attenuation of the x-rays in the breast. Thus, while speculative, it may be possible to significantly reduce the dose needed to image the breast if an efficient imaging system can be constructed.

In this grant, we proposed to investigate the potential of x-ray polarization imaging. We proposed to build an x-ray polarimeter (a device designed to measure polarization) and determine the factors that affect its design. We plan to perform fundamental experiments regarding x-ray polarization to determine whether the effect is sufficiently large to allow it to be used to produce images. We also wish to measure the ability of key biological materials, including breast tissue, to alter the polarization of x-rays, and determine the accuracy with which we can measure this effect.

This research, while quite fundamental in its nature, has the potential for a significant impact in breast cancer diagnosis. The use of effects related to the polarization of x-rays is a largely unexplored field. Thus imaging based on this mechanism would represent a new way of non-invasively studying the human body.

These considerations are, quite clearly, speculative, but the program described in the grant would give the experimental data necessary to clearly understand the benefits and limitations of attempting to image tissue using polarized x-rays. This annual report presents our research to date.

2. Body

2.1. Statement of Work

The work for this grant was divided into four tasks. They are outlined as follows:

TASK 1: DESIGN AND DEVELOP X-RAY POLARIMETER

The proposed x-ray polarimeter design is based upon an apparatus whereby the distribution of the scattered radiation is used to measure the polarization. The initial task in this project is to design and build this polarimeter. The following steps are necessary in this task

Mechanical Design: A mechanical design for the gantry will be made.

X-ray source: The exact operating conditions of the polarimeter will need to be calculated and appropriate x-ray equipment assembled.

Analyzer: The analyzer acts to scatter the polarized x-rays. Performance is dependent upon the composition, shape and size of the analyzer, which will be tested with a theoretical analysis and experimental verification.

Beam stop: A carefully designed beam stop is necessary. The efficacy of various beam stop designs will be investigated using EGS Monte Carlo code (or equivalent).

Shielding: A critical element to this experiment is the shielding. The shielding, collimator, and material holder will have to be carefully designed with a series of Pb baffles to avoid excessive scatter from objects other than the analyzer. If necessary, EGS Monte Carlo simulations will be applied to aid in the design of the shielding.

Detector and associated electronics: The choice of the detectors and detector electronics will be made based upon estimated photon fluence, necessary signal-to-noise ratio (SNR) to observe polarization, cost, and other factors.

Control computers and operating software: It shall be necessary to write software that can operate the x-ray generator, motion systems, and detector readout (MCA or electrometer) in a coordinated fashion.

Data Analysis Software: It shall be necessary to write software to analyze the data obtained from the polarimeter.

Verification of Operation: As the system is designed, built and assembled, it shall be necessary to validate the operation of each component and of the system as a whole. We expect this to be an iterative procedure, which will require some time.

TASK 2: VALIDATE THE POLARIMETER DESIGN

Detector Calibration: Since four detectors are to be used in the experiment, and yet the data is to be combined, we will need to calibrate the detectors.

Data Fitting: It is necessary to fit the data obtained in these experiments to determine the polarization angle. Algorithm to perform this operation must be designed.

Linearity of Polarization Measurements: We propose to measure polarization as a function of thickness for some key materials.

<u>Effect of kVp, target material and filtration:</u> To determine the operating conditions for the polarimeter, we will measure P_{pol} for a variety of combinations of kVp, filter material and filter thickness. The energy spectrum of the scattered beam will be measured for each combination.

<u>Effect of kVp and atomic number:</u> The effect of kVp on the optical activity measured for certain key materials (e.g., as suggested above), will be tested. In addition, the effect of binding energy on polarization will be tested by measuring the polarization obtained with high-Z materials above and below the K-edge.

TASK 3: TABULATE OPTICAL ACTIVITY FOR COMMON MATERIALS

We will catalog the optical activity of various biological and inorganic materials.

TASK 4: POSTULATE THE DESIGN OF AN IMAGING SYSTEM(S)

Using the information gathered above, we shall postulate upon the likelihood of success of polarization imagers, and evaluate a variety of possible designs.

2.2. Administrative Note

Effective February 1st, 2003, Dr. Maidment resigned his position at Thomas Jefferson University and began working at the University of Pennsylvania. At that time, Dr. Maidment requested that the grant be transferred to the University of Pennsylvania. The grant transfer was approved by the DOD in a letter dated April 14, 2004. A grant account at the University of Pennsylvania was formally opened on the May 19, 2004, covering the period 01-Mar-04 to 26-June-06.

In addition to the transfer of the account, Dr. Maidment has moved his laboratory from temporary quarters in the Stemmler Building, to permanent quarters in the Chemistry Building (Suites 283, 286 and 287, 33rd and Spruce Streets). The suites encompass almost 1000 sq. ft. of office and laboratory space. The laboratory is lead-lined to allow x-ray experiments. The laboratory is equipped with excellent power and air conditioning systems, which are ideal for the planned x-ray experiments. An new x-ray generator and x-ray tube have been purchased for this project.

Finally, after many years of staffing shortcomings, Dr. Maidment's lab will soon be at full strength. The lab consists of Dr. Michael Albert, Dr. Predrag Bakic, Dr. Harry Kao, and Dr. Ann-Katherine Carton. Dr. Carton will be arriving from Belgium to begin work August 16th. She will be the primary person assigned to this research project.

The combination of moving the laboratory to the University of Pennsylvania; designing, building and moving into new laboratory space; obtaining appropriate equipment; and selecting appropriate people has taken some time. However, the work on the grant can soon begin in earnest.

2.3. Background:

2.3.1. Polarization and Optical Activity:

Most biological materials are optically active to visible light. Like other materials, optically active materials can refract, absorb and scatter light, but in addition they respond differently to radiation, depending upon whether it is left or right circularly polarized. The differential absorption of light of these two polarizations is called circular dichroism, and the differential refraction is called circular birefringence, which for plane-polarized light is observed as optical rotation. Plane polarized light is composed of equal amplitudes of left- and right-polarized light. The magnitude of the optical rotation of plane-polarized light is proportional to the difference between the indices of refraction for left and right circularly polarized light and the thickness of the optically active material.

2.3.2. X-ray Polarization

Like other forms of electromagnetic radiation, x-ray photons can exhibit phenomena related to polarization. Bremstrahlung x-rays produced by electrons accelerated from the cathode to the anode of an x-ray tube are partially plane-polarized with the electric field vector parallel to the cathode-anode axis [Dyson90, Agar79]. Classically, an accelerating or decelerating charged particle emits radiation whose electric field vector (at each point in space) is coplanar with the axis of acceleration or deceleration [Barut80, Rohr65, Schwing98, Jackson99]. The physical reason for this geometric fact is clearer in the related process of an electron being scattered by a photon, as it is the electric field of the incident (or emitted) photon which is chiefly responsible for accelerating (or decelerating) the electron. By way of comparison, synchrotrons produce coherent, circularly polarized radiation.

The Bremsstrahlung radiation of diagnostic x-rays is on the order of 5-10% polarized, with greater polarization for x-rays whose energy is nearly that of the incident electron. Lower energy x-rays are produced by processes in which the electron's direction might have changed prior to emission of the x-ray, and thus have less polarization. These effects were experimentally documented as early as 1905 [Barkla05], as reviewed in [Steve57]. More recent research has tended to deal with thin targets (for example, [Kuck73]) so that the kinematics at the interaction vertex are well defined. A measurement of polarization from a Phillips x-ray tube [Staun78], in a study aimed at crystallographic applications, showed general agreement with the older results. Similar agreement was reported in an abstract [Slivin71].

2.4. Experimental Results

2.4.1. Poly-energetic x-ray Polarimeter Design

Although there are many ways to measure the polarization of mono-energetic x-ray beams, there is one prime method of measuring polarization of *poly-energetic x-ray beams*. This polarimeter design relies upon the angular distribution of the scattered beam to measure the polarization of the incident beam. Such a polarimeter is shown in Figure 1. It consists of a collimated x-ray tube, an analyzer, and two x-ray detectors at right angles. To measure polarization rotation by a sample material, the material must be placed in the primary beam, and the detectors must be mounted on a rotating gantry. In

such experiments, the intensity of the scattered radiation recorded by the detectors would have a sinusoidal angular dependence.

The angular dependence of x-rays scattered from a polarized beam can be understood at the classical level. If a plane-polarized wave is incident upon a charged particle, the resulting acceleration **a** of the particle will be parallel to the electric vector $\mathbf{E_{in}}$ of the incident wave. The electric field component of the resulting scattered radiation at a distance **R** away from the scatterer in the direction $\bar{n}$ (a unit vector) will be proportional to $\bar{n} \times (\bar{n} \times \mathbf{a}) / \mathbf{R}$ [Barut80, Rohr65, Schwing98, Jackson99]. This formula has a simple geometric interpretation in that the electric field vector is proportional to the acceleration projected onto a plane perpendicular to the line of sight from the field point back to the scatterer. For a wave moving along the z-axis and plane polarized so that the electric vector lies along the x-axis (parallel to the anode-cathode axis), the angular distribution of scattered radiation per solid angle will have the form

$$\frac{d\Phi}{d\Omega} = r_o^2 \left[1 - \sin^2(\theta) \cos^2(\phi) \right]$$

where θ is the polar angle ($0 < \theta < \pi$) and ϕ is the azimuthal angle ($0 < \phi < 2\pi$).

The azimuthal variation is maximal for scattering at 90° relative to the incident radiation ($\theta = \pi/2$). In this plane, scattering would be 100% suppressed at $\phi = 0$ or π (the direction of the electric field vector $\mathbf{E_{in}}$ of the incident beam) if the beam were completely polarized.
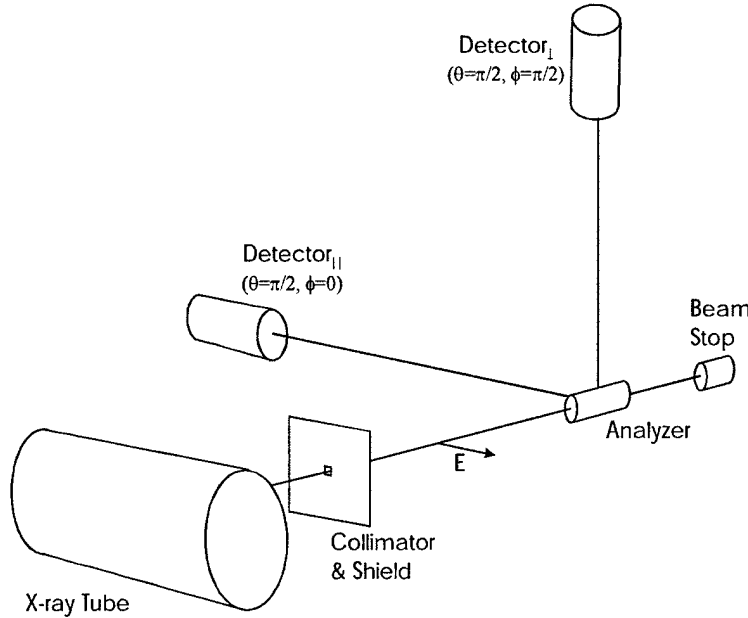

Figure 1: Schematic of the Polarimeter

For incompletely polarized beams, the azimuthal variation will be less pronounced. Using radiation scattered at 90°, if $I_{\parallel}$ represents the intensity of the scattered radiation in the direction parallel to the preferred direction of the electric field vector ($\phi = 0$) and $I_{\perp}$ represents scattering in the orthogonal direction ($\phi = \pi/2$), the degree of planar polarization of the incident beam can be quantified in terms of $P_{pol} = (I_{\perp} - I_{\parallel}) / (I_{\perp} + I_{\parallel})$ which would

be 1 for a completely plane-polarized beam and is on the order of 0.05-0.1 for conditions similar to clinical x-ray tubes.

2.4.2. Poly-energetic Experiments:

Barkla [Barkla05] and others have demonstrated polarization of conventional x-ray tubes. However, such experiments have been chiefly concerned with the nature of the Bremsstrahlung process or, for the earliest experiments, the nature of x-rays themselves. Work on optical activity in the x-ray region has generally used low energy x-rays (<1keV). The only known measurement of optical activity at diagnostic energies is for quartz ($3.5°±1.3°$ at 19 keV) [Hart81].

We have conducted experiments using an apparatus similar to that shown in Figure 1. The analyzer consisted of a Lucite rod 2.5 cm diameter, and 13 cm long. The analyzer was positioned 40 cm from a tungsten target x-ray tube (Siemens Bi 150/30/50R), operated at 100 kVp and 100 mAs. The x-ray beam was collimated by a 6 mm diameter circular aperture, located 20 cm from the x-ray source. Thus, the irradiating beam was 12 mm in diameter at the analyzer. Two ion chambers where mounted at right angles to the beam, and at right angles to each other ($\theta=\pi/2$, $\phi= 0$ and $\pi/2$), 60 cm from the analyzer. The primary photon fluence incident upon the analyzer was estimated to be 2×10^{11}, while the scattered fluence at the detector in the direction perpendicular to polarization was 2×10^6 cm^{-2}. We have thus observed x-ray polarization, measuring $P_{pol}=0.10$.

2.4.3. Pseudo Mono-energetic Polarimeter Design

Due to advances in our work with molybdenum Ka radiation sources, we have begun to examine a possible polarimeter design based on a molybdenum x-ray source and a calcite crystal placed at 45° to the x-ray beam. The calcite will reflect the Ka radiation at a Bragg angle of 45° (reflected beam is emitted at 90°) on the 1 1 0 1 plane of the crystal, so that the reflected beam is 100% polarized. The complete polarimeter is shown in Figure 2. The polarimeter consists of an x-ray tube, a reflecting crystal, a series of collimators to isolate the x-ray energy desired and to eliminate scattered radiation, a sample holder, and a detector consisting of an x-ray image intensifier and CCD camera. A sample image of the reflected x-ray beam is shown in Figure 3, with a sample polarization scatter image is shown in Figure 4.

This has the advantage rather than attempting to measure changes in polarization with a signal of 10%, the signal has 100% amplitude. There are two problems with this technique. First, only a small fraction of the incident x-rays are so reflected, thus the signal recorded is very weak. Secondly, the x-rays scattered by the sample need to be scattered at close to 90° to show 100% polarization. This further reduces the number of scatter events that can be successfully recorded. In the image shown in figure 4, the scatter angle is about 10°. Thus, we were unable to convincingly demonstrate polarization effects. As a result, we have now decided to pursue our original design for the polarimeter.
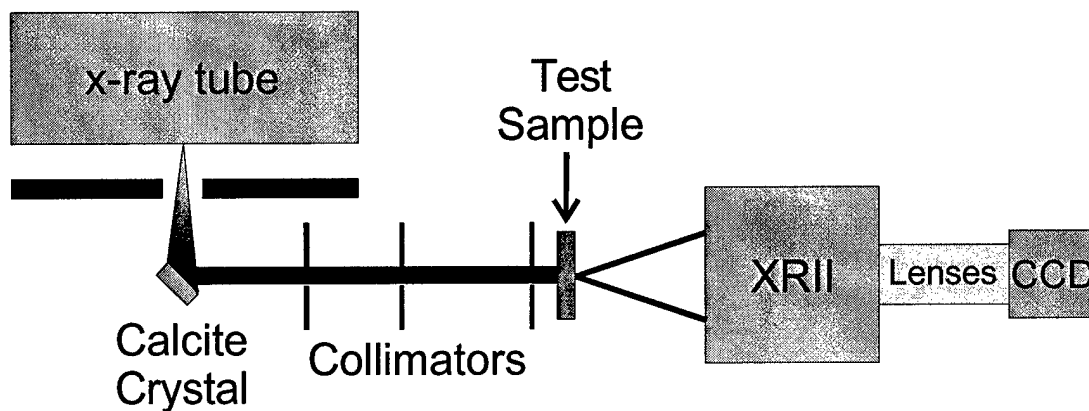
Figure 2: The schematic for the mono-energetic polarimeter. The x-ray tube produces a poly-energetic spectrum. The calcite crystal reflect the Ka radiation (~17.3 keV) at 90 degrees. This polarized, mono-energetic beam is passed through a series of collimators and hits the test sample. The test sample then scatters the incident x-rays. The angular distribution of the scattered x-rays varies due to the x-ray polarization. This image is produced with the x-ray image intensifier (XRII) and then recorded by the CCD.
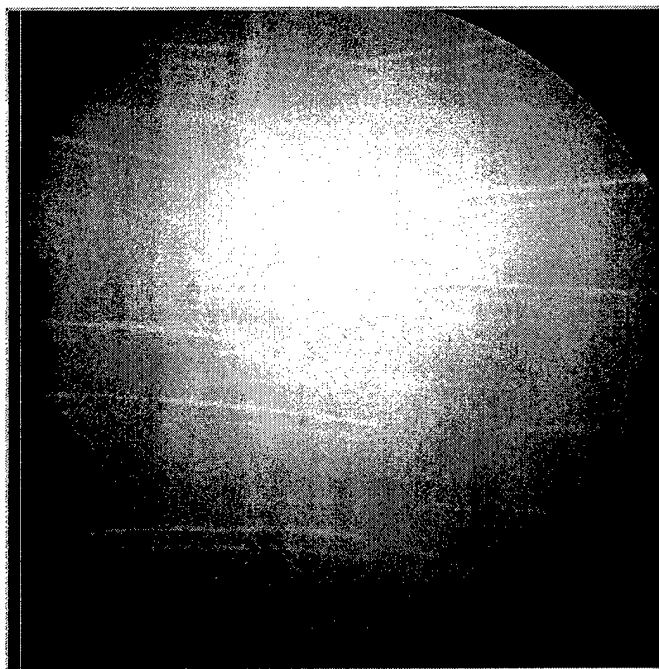

Figure 3: An image of the reflected x-ray beam without intervening collimation. The Ka lines are clearly seen. Multiple lines are seen due to imperfections in the crystal. A cross-section through this image and a similar image filtered with niobium is shown in Figure 5.
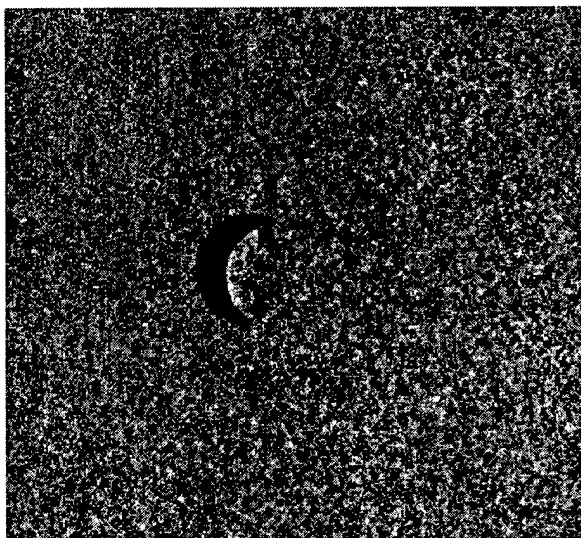
Figure 4: A single ka line was selected to interrogate a thin layer of wax. Shown is the beam scattered at an angle of approximately 10 degrees. (The crescent shape is an artifact). The beam appears to scatter more in the vertical direction as expected. The image, however, is quite noisy due to limitations on x-ray exposure.
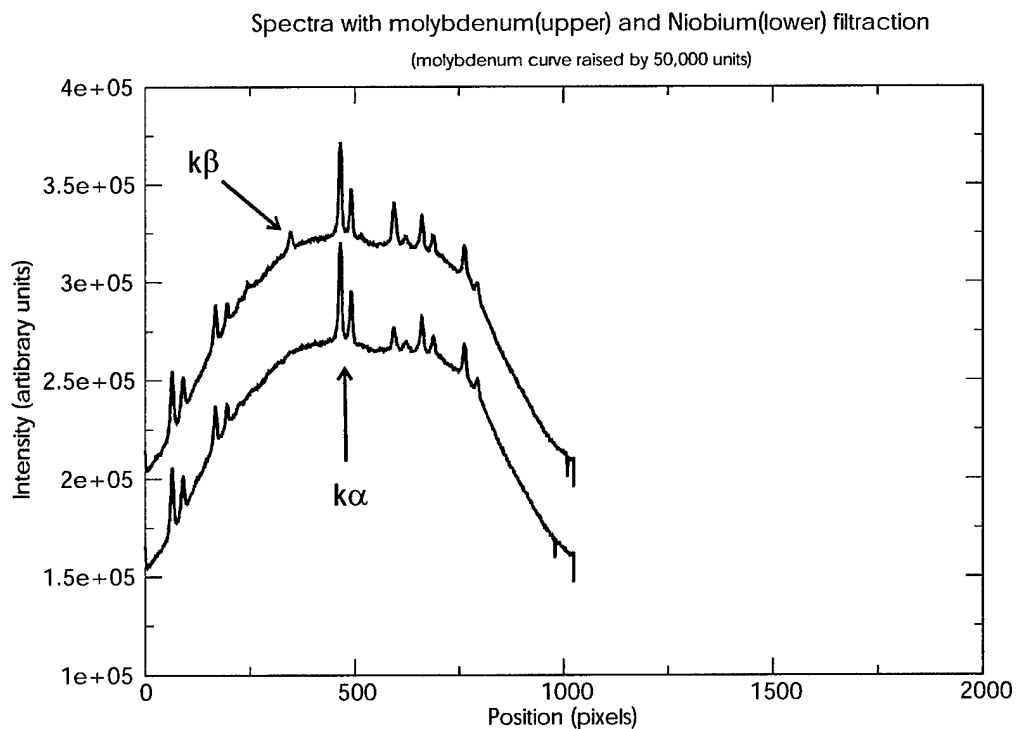

Figure 5: The intensity of as a function of position across the x-ray detector. The two graphs differ by the beam filtation. One allows kß radiation to be imaged, the other does not. Note that the kß lines are missing in the one graph. The two graphs are displaced for illustrative purposes only. Due to imperfections in the crystal used, there are multiple replicates of the K lines.

3. Key Research Accomplishments:

We are now ready to construct the x-ray polarimeter to be used in this grant. The work was interrupted due to our move from Thomas Jefferson University to the University of Pennsylvania. However, the grant has now been transferred, we have moved into our new laboratory, and we have hired an excellent Research Associate to work on this project. Dr. Carton will arrive Aug 16th from Belgium and we expect the work to begin immediately.

4. Reportable Outcomes:

None to date.

5. Conclusions:

We have successfully been able to produce polarized x-ray beams and have begun to characterize the detectors used. We will soon begin permanent construction of the selected design.

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7. Appendices:

None.